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The dynamics of solar PV costs and prices as a challenge for technology forecasting

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ABSTRACT

An effective energy technology strategy has to balance between setting a stable long term framework for innovation, while also responding to more immediate changes in technology cost and performance. Over the last decade, rather than a steady progression along an established learning curve, PV costs and prices have been volatile, with increases or plateaus followed by rapid reductions. The paper describes, and considers the causes of, recent changes in PV costs and prices at module and system level, both international trends and more place-specific contexts. It finds that both module and system costs and price trends have reflected multiple overlapping forces. Established forecasting methods – experience curves and engineering assessments – have limited ability to capture key learning effects behind recent PV cost and price trends: production scale effects, industrial re-organization and shakeouts, international trade practices and national market dynamics. These forces are likely to remain prominent aspect of technology learning effects in the foreseeable future – and so are in need of improved, more explicit representation in energy technology forecasting.

Contents

1. Introduction

The pressing need to decarbonize energy systems poses multiple policy challenges – high among them, developing and maintaining a support package for low carbon technological innovation [1–3]. In defining such policy support multiple technical, economic, political and societal forces have to be taken into account in order to deliver a balanced energy technology strategy and to enable emerging technologies to progress along the 'innovation chain' from R&D to large scale deployment. Crucial element in such challenge is a robust assessment of emerging energy technologies' cost-competitiveness, in particular by accounting for their possible future cost and performance trajectories. Indeed, a successful energy technology strategy must be able to balance between the need to set a stable long term vision for innovation as part of overall energy

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system change, while also being responsive to more immediate (and perhaps unexpected) changes in technology cost and performance.

This challenge is here considered and discussed in the context of solar photovoltaics (PV). Solar PV is a technology which has shown decades-long learning (in terms of reduced manufacturing costs and improved performance), under the benefit of sustained policy support; as such, it is seen a prime exemplar (along with wind) of a renewable energy technology learning curve [4]. Over the last decade, however, rather than a steady progression along its established learning curve, PV production costs have experienced increases followed by rapid reductions and PV prices have been increasingly volatile.. This volatility has created problems for policy, with 'PV bubbles' being seen in a number of European countries with strong market creation support measures [5,6]. The recent history of PV therefore highlights the dilemma of technology policymaking for long term system change, while being responsive to short term market fluctuations.

The paper considers this dilemma in terms of its implications for technology assessment and forecasting methods. It looks into recent changes in PV production costs and prices at module and system level (both international trends and more country-specific contexts) and it considers the causes of these changes – going beyond simple 'headline' causes to see cost and price trends in PV modules and systems as reflecting multiple overlapping forces. In particular, it addresses the technology forecasting methods available (both aggregated – experience curve - and disaggregated – engineering assessment - methods) and discusses the extent to which they have been able to describe and anticipate such cost and price trends.

The framing of the paper is mostly international/global, as is appropriate for a study of PV innovation dynamics given that PV modules are manufactured and traded on a global market. PV system prices are by contrast more affected by national/local implementation conditions, so for the discussion on PV system cost dynamics attention is given to selected specific PV markets, with a particular focus to United Kingdom.

Section 2 firstly provides an introduction to the two main cost forecasting methods considered and their use for PV cost assessment. Sections 3 and 4 discuss PV module and system cost and price trajectories, main drivers behind them and to which extent price trends have been predicted by the available forecasting methods. Finally, Section 5 draws some conclusions on the implications for technology forecasting methods and for policy making.

2. PV costs assessment and forecasting methods

There is a wide range of contributions to the PV cost reductions literature; these can be broadly grouped in two main categories. Firstly, *experience curves* (*or learning curves*), where cost reductions are analyzed as function of market and production capacity expansion, and future cost reductions are estimated by projections of historical trends, bearing in mind the likelihood of historic drivers continuing into the future. Secondly, *engineering assessments* (or system component analyses) are 'bottom up' analyses which use engineering-based estimates to assess the contribution of different technology system components to the overall costs, and how improvements in efficiencies and refinements in production processes affect their future trajectories. Each method and its use for PV cost assessment are now discussed in turn.

2.1. Experience curves and their use in PV technologies forecasting

Experience curves describe a quantitative relationship between cumulative production and the 'unit cost' of a given technology (measured as either capital cost or cost of energy produced). Experience curves are generated by measuring the effect of a doubling of cumulative production on the unit cost (or price). The resulting percentage change is called the *progress ratio*. A related and frequently used indicator is the *learning rate*, the complement to the progress ratio. Experience curves have been widely used to describe historical trends and performance of energy technologies [4,7–12] as well as for estimating the future costs of energy technologies based upon expected market development and future production capacity. A technology's future cost reduction potential can be inferred by applying a historically observed progress ratio/learning rate to projected market growth [8,13–16]. Alternatively, experience curves are sometimes used to assess the market expansion needed to achieve a certain target cost reduction (e.g. a 'break-even' cost target) as well as the total learning investment and the time needed to achieve the given cost target [4,11,13,17–19].

Experience curves are an effective mean of capturing long term historic cost trends and have been widely used to describe historical cost trends of technologies and to inform policy decisions. They can also facilitate the representation of progressive learning and technology change into energy modeling and scenario analysis – providing a quantitative illustration of cost reduction potential and the role of innovation in long term change.

However, the limitations of experience curves in technology forecasting have been repeatedly identified in the literature. At a basic conceptual level, learning by experience (the assumed primary learning effect in learning curves) can only partially explain cost reductions and the multiple, complex drivers of cost reductions cannot be fully captured by a simple functional relationship between capacity installed and unit cost [7,14,20–25]. In particular, experience curves are deemed ill-suited to predict discontinuities in learning due to e.g. technological breakthroughs, market structural changes, effect of knowledge spill over from outside the industry as well as possible future barriers to development [25]. Indeed, the tendency of experience curve-based forecasts is to project forwards historically observed cost/price trends – and implicitly therefore, the drivers behind historic trends. Even within an established design, however, significant changes of learning rate may be seen, reflecting different stages of maturity.

Particular concerns have been raised about projecting forwards learning rates in modeling exercises. Several studies have highlighted how discontinuities and uncertainties in the future learning rates can non-linearly propagate through energy policy models [26] and are not fully acknowledged when used to inform policy decisions [4,24,25,27]. Given demands for accelerated energy system transformation, there may well be an increased likelihood of future discontinuities and step-changes in the energy technologies, and the risk is that such changes are not fully captured and anticipated by energy modeling and policy decisions informed by them.

There is a wide range of studies applying experience curves to PV technologies. The majority of PV experience curves are built from data for *1st generation* crystalline silicon (c-Si) PV, which is historically the conventional PV technology (see also Section 3). However, other PV technologies such as *2nd generation* inorganic thin film or novel *3rd generation* PV technologies (which includes a range of novel technologies at pre-commercial stage: from demonstration, e.g. multi-junction concentrating PV, to novel concepts still at R&D stage e.g. polymer cells, quantum-structured PV cells [28]) are emerging and are likely to follow different learning path than conventional c-Si PV (see also Section 3.1). In principle, an aggregated experience curve could be developed to encompass conventional c-Si and emerging PV technologies. However, very little time series data exist for emerging PV technologies, so that experience curves cannot be built for them with any degree of confidence (other than in a highly speculative scenario fashion).

Another limitation of PV experience curves is that they generally use PV module *prices* as a proxy for *production costs*. This is because PV manufacturers closely guard their design, construction, and operations costs and, as a consequence, it is not straightforward to build up a time series for production costs. However, module prices are the result of a combination of production costs and margins which are affected by market forces such as demand/supply dynamics, companies' strategies and levels of competition. This approximation thus limits the ability of experience curve analysis to disentangle drivers purely affecting production costs from market forces which have instead an impact on module prices (as further discussed in Section 3).

PV experience curves have been mainly developed for PV *module* prices, yet PV technologies are more accurately framed as a compound learning *system*, including balance of system (BOS) costs. BOS usually refers to all PV system components and cost elements other than the modules, including technical components such as the DC-AC inverter, mounting structures, cables and wiring, battery (for off-grid systems), metering (for grid-connected applications) as well as installation, design and commissioning costs. Thus, learning rates based on modules-alone are not representative of PV system learning, and system level cost reductions cannot be easily attributed to individual components. There is relatively limited quantitative evidence of the drivers of cost reductions at the BOS level, reflecting the contextual variability of BOS costs: such costs differ by application, e.g. grid-connected versus off-grid, and between different grid-connected applications (roof mounted, ground mounted, building integrated PV) – see also Section 4. Where reliable BOS time series data is not available, the use of experience curves as descriptors of past and possible future trends is limited. Rather like the case of emerging PV module technologies discussed, data limitations mean that reliable experience curves cannot be built for countries with emerging and volatile PV markets.

Moreover, there are also wide regional differences in system design and implementation and installation practices, reflecting country specific market, policy and regulatory conditions. Framed at the system level, PV learning rates cannot be simply transposed between locations with different regulatory and market conditions. This magnifies uncertainties for forecasting system level costs in countries with a nascent PV sector, where robust time series data is unlikely to be available.

The implications of these limitations and uncertainties for PV technologies cost assessment are further discussed below: Section 3 discusses implications for module forecasting and Section 4 further discusses challenges in PV system cost predictions by taking the UK as an exemplary case.

2.2. *Engineering assessment of PV technologies*

Given their highly aggregated and long-run nature, experience curves do not offer detailed causal explanation regarding technology cost and performance dynamics. Engineering assessments, by contrast, disaggregate a technology system into its component parts, for a detailed analysis of potential/prospective techno-economic improvements, and their implications for cost reductions. It may also assist in developing cost projections for those novel technologies for which historical data is not available – possibly as a complement to experience curve analysis. Engineering assessments are less commonly used than experience curves, but have found application in more specific analyses of the impact of technological innovation on future costs [24].

Engineering assessment-based estimates of PV costs have been developed by academic studies [29–31], by PV technology road-mapping activities [32–35] and, increasingly, by companies and market analysts [36–41]. These studies generally involve a combination of technology specific data gathering and expert elicitation. The latter is particularly important in overcoming data constraint issues imposed by manufacturers' confidentiality concerns regarding their product design and production costs. Neij distinguished between bottom up engineering studies and more intermediate expert judgments used for 'long-term development paths' [27]. However, such judgements entail a degree of uncertainty and possible biases, including the likelihood of expert 'appraisal optimism' [42].

3. Assessing PV module cost and price trajectories

This section reviews PV module cost and price trajectories and some of the major drivers involved; after a very brief recap of longer term trends, the focus is on recent cost and price trends over the last decade. It then discusses the use of established forecasting methods and to which extent they predicted costs/price trends and variability, in particular in the more recent years. To avoid confusion, it is important to distinguish here between production costs and prices of PV modules. The former are the costs of producing a PV module whereas the latter are the price charged to the final end customer, resulting from a combination of production costs and companies' mark-up (price-cost margin). As such module prices are also affected by market forces such as demand/supply dynamics and levels of market competition, thus drivers which goes beyond production costs themselves. Nevertheless, module prices are often used as proxy for production costs within the literature on the economics of PV (as for example in experience curve literature – see Section 2.1), due to the fact that PV module price data is available in the public domain whereas access to production costs data is generally limited by confidentiality issues. Therefore, in what follows drivers affecting production costs are treated separately from market dynamics affecting module prices. However, due to the limited availability of production costs data over time, module prices are still used sometimes in the discussion as evidence of changes in production costs.

3.1. *Module production cost and price trends*

PV module manufacturing costs and, as a consequence, prices have fallen dramatically since the 1970s, reflecting the progressive development and deployment of *1st generation* crystalline silicon (c-Si) modules – the conventional PV technology which still accounts for the bulk of the PV market (about 87% in 2011 [43]). The first substantial drop in PV module costs occurred in the mid-1970s, when PV moved from space to terrestrial applications, allowing for reduced demand for device quality and reliability, greater product standardization and increased market competition [44,45]. This reduction in costs led to a decrease in c-Si module prices from $90/Wp in 1968 to $15/Wp in 1978. Subsequently, c-Si costs continued to decrease over time, and increased device efficiency and manufacturing scale were judged to be the major cost reduction drivers, accounting respectively for 30% and 40% of the reduction [14]. This allowed c-Si module to reach prices in the range of $5/Wp by early 2000s [46].

Over the last decade the PV sector has expanded dramatically thanks to demand pull policies implemented in specific countries (including Italy, Germany, Spain and France).Worldwide cumulative installed capacity has been growing from 1.4 GW in 2000 to over 67 GW in 2011 [47]. In the mid-2000s, under sharp increases in demand for PV modules the PV manufacturing industry experienced a serious bottleneck – a silicon feedstock shortage which caused silicon prices to rise, reversing historical cost reduction trend (Fig. 1). However, the silicon shortage also stimulated innovation efforts across the PV system – in R&D and

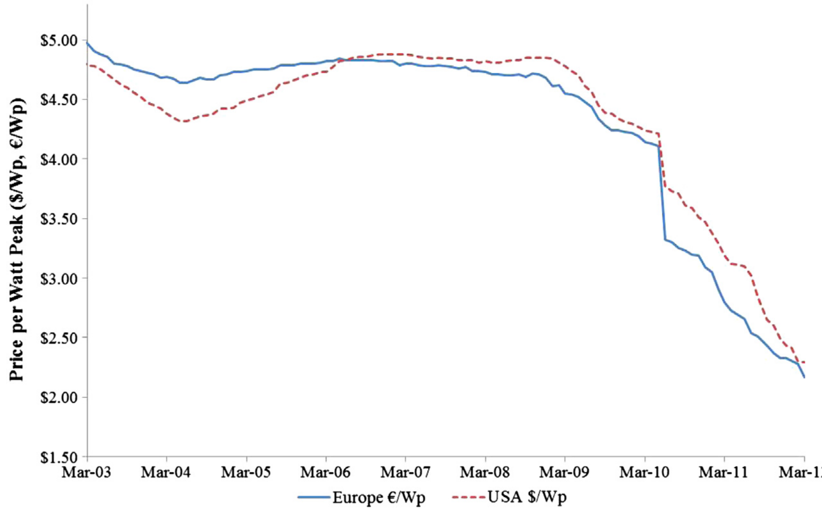


Fig. 1. PV module retail price index (2003–2012, $€_{2012}$ and $\$_{2012}$). *Note*: figures presented are average retail prices in Europe and the USA based on a monthly online survey. They encompass a wide range of module prices, varying according to the module technology (with thin film modules generally cheaper than c-Si), the module model and manufacturer, its quality, as well as the country in which the product is purchased. For example, in March 2012 average retail module prices were respectively 2.29$/Wp in USA and 2.17€/Wp in Europe, but the lowest retail price for a crystalline silicon solar module was 1.1$/Wp (0.81€/Wp) and the lowest thin film module price was 0.84$/Wp (0.62€/Wp).
Source: [46]

manufacturing to improve material utilization (through both lower silicon consumption and module efficiency increases) [48]. In addition, it drove new investments in feedstock production and increased R&D efforts in developing cheaper ways to produce silicon (e.g. production of less pure 'solar grade' silicon) [28,32,33,35]. In the late 2000s, silicon feedstock prices more closely reflected production costs, and feedstock production capacity expansion created oversupply, driving silicon prices rapidly downwards (spot prices fell as low as 35$/kg in late 2011, compared to spot prices of hundreds $/kg in the previous years) [48–50]. Cheap silicon feedstock then fed through to a dramatic fall in c-Si module manufacturing costs from the late-2000s and early 2010s [51]. Improvements in manufacturing processes also contributed to module cost reductions and module production has become more automated, with a gradual move away from batch processes toward in-line, high throughput, high yield processing. Another factor on cost reductions has been industry restructuring, especially supply chain integration [52]. For many years, PV companies tended to specialize in a single activity in the value chain. In recent years, the largest c-Si PV manufacturers have integrated both up-stream and down-stream, allowing them to reduce overhead costs, to capture margins at every stage of the PV module value chain and strengthening their ability to purchase silicon feedstock or wafers at cost prices.

The market expansion of the last decade has also driven a dramatic increase in c-Si production capacity and average plant size, with consequent economies of scale (in particular in sourcing materials) and reduction in manufacturing costs. In 2007 average plant size was c. 100 MWp.a.; over the next few years this quickly increased to 500–1000 MWp.a. range[1]. Much of the recent growth in production capacity has been in China and Taiwan, which by 2010 accounted for about 50% of world-wide production [54], and China only could account for more than 60% in 2015 if all announced capacity expansion plans are realized[55]. It has been previously shown that, back in 2005, Chinese companies with production capacity under 10 MW were struggling to compete with larger manufacturers as not able to secure silicon and other materials at low enough prices (e.g. as unable to rely on long term contract for silicon) [56]. Recent contributions have instead highlighted how scale and integration achieved in the recent years have allowed Chinese manufacturers to source materials at much lower prices (e.g. some estimate at least a 10% discount compared to US competitors[57,58]).[2]

The silicon bottleneck and consequent production cost increases for c-Si technologies in the mid-2000s also triggered a new wave of investments in emerging (2nd generation) thin film PV technologies, with production capacities reaching the MWs range, and turnkey production lines with high cost reduction potential being developed. Thin film module average selling prices declined from 2.75$/Wp in 2005 to 1.35$/Wp in 2010 [60]. Thin film PV modules became the cheapest on the market and least expensive to manufacture. Indeed, First Solar (a major thin film manufacturer, producing cadmium telluride – CdTe – modules) was the first PV manufacturer to reduce manufacturing costs below the $1/Wp cost threshold, in 2009 [38].

These technological and manufacturing improvements and relative cost reduction have fed into module prices, which, apart from a temporary increase in mid-2000s due to the silicon feedstock bottleneck, have been decreasing dramatically, particularly from 2009 onwards (see Fig. 1).

In less than 2 years, between the mid-2010 and March 2012, c-Si module prices fell by about 45% [46]. However, such drop in module prices has also been heavily driven by market dynamics; hence it can only partially be explained by reductions manufacturing costs themselves. Indeed, the pace and extent of these reductions were largely unexpected (see also discussion in Sections 3.1 and 3.2) and were correlated to the dramatic market expansion and a strong oversupply imbalance recently experienced by the PV industry. Indeed, the high demand and profit margins in the second half of the 2000s have driven high levels of

[1] For example, JA Solar, the second largest PV manufacturer in the world has established a PV module production facility in Fengxian, Shanghai, with an annual capacity of 1.2 GW [53].

[2] Although it is also worth mentioning that vertical integration can and has sometimes been a disadvantage in the recently very volatile market (characterized by sudden and unexpected changes in both silicon and module prices – see further discussion below) as manufacturers vertically integrated have not been able to take advantage of opportunistic feedstock material sourcing on the spot market, and were rather burdened by long term contracts [59].

investment in new production capacity, with new companies and countries entering the market [61,62]. Between 2000 and 2010, PV module production increased more than 30 fold, with annual growth rates above 40% after 2006 [63]. By 2009, many analysts expected a shift from a supply constrained to a demand-constrained market [64,65] and production overcapacity along the whole module value chain started to impact the market in 2010 and continued over 2011 and 2012 leading to dramatic drop in global module prices. Worldwide production capacity has been above annual installations since 2010 (in 2012 annual installations have been about 30 GW versus a total production capacity of about 50 GW) [55,66,67].

As previously highlighted Chinese PV industry has been expanding very quickly in the recent years, with production capacity increasing from just above 100 MW in 2005 to over 21 GW in 2010, the majority of which in c-Si module manufacturing [43,56,58]. Chinese manufacturers have indeed been largely responsible for the recent c-Si module price reduction being able to supply global market with much lower price modules than European, Japanese or US manufacturers. Spot market prices for c-Si modules are still currently roughly 30% lower in China than Europe and Japan [68]. Some industry experts have suggested that modules were being sold at very reduced margins or below production costs [69,70], triggering industry consolidation, with several companies filing for bankruptcy since late 2011, and international controversies over module pricing. Both the US and the European Commission have launched anti-dumping investigations into imports of photovoltaic cells, wafers and modules from China [71]. In June 2012 the US have imposed anti-dumping tariffs of just over 31% on crystalline silicon PV cells from major Chinese producers, after ruling that exporters sold product in the US at “less than fair value” [72]).

Overall, it is not straightforward to fully disentangle module price reductions due to reduced production costs related to device and production processes improvements and economies of scale along the PV module value chain from market demand/supply dynamics, including manufacturers strategies in materials sourcing and other factors such as access to cheap capital for Chinese manufacturers and industry ‘dumping' strategies. Other contributions explore this issues more in detail [52,57,58].

These dramatic and largely unexpected c-Si module price reduction have also affected the market positioning of thin film technologies, which are now struggling to keep the pace with the incumbent/conventional technology. With margins dramatically reduced several thin film companies have been going out of business and are looking into new competitive strategies to go back on track (e.g. through product differentiation and alternative/niche applications).

3.2. Experience curves forecast of PV module production costs

Experience curves are conceptually constructed to describe the relationship between cumulative production and unit production costs of PV, thus in what follow the ability of experience curves to forecast PV module production cost reduction is discussed; this despite the fact that PV module prices are in practice used as proxy for costs (e.g. Fig. 2). Table 1 summarize learning rate results from a selection of PV experience curves studies.

Estimated learning rates vary considerably across the studies, according to the reference dataset and the scope of the analysis. Indeed, although average historical PV learning rates are in the order of 20%, a closer look at the data shows high variability across time [4,26,27]. In general, learning rates estimates have been below 20% for the late 1980s-early 1990s and above 20% for the late 1990s (see also Fig. 2), the latter not coinciding with a high market growth rate, but possibly instead reflecting the impact of R&D investments made before 1990s [9,14]. Similar fluctuations have been experienced in the last decade, as described in the previous section, with lower learning rates under silicon feedstock shortage and higher rates in the more recent years [4]. As described above, these more recent changes have been associated with changes in the structure of the PV supply and manufacturing industry, thus affecting PV module prices more than underlying production costs.

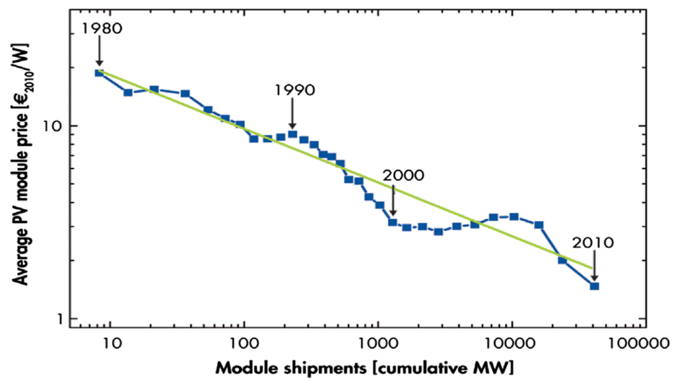


Fig. 2. PV module experience curve (1980–2010). *Note*: PV module spot market prices are here plotted against cumulative module sales (log scale). The green curve is a fitted trend of the historical price data. . (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.) *Source*: [33].

Table 1
Learning rate variations among selected studies.[a]
Source: [5,7,15,44,73–77].

Study authors	Learning rate (%)	Years	Scope
Williams and Terzian (1993)	18.4	1976–1992	US
Cody and Tiedje (1997)	22	1976–1988	US
Schaeffer et al. (2004)	20	1976–2001	Global
Harmon (2000)	20.2	1968–1998	Global
Maycock and Wakefield (1975)	22	1959–1974	US
McDonald and Schrattenholzer (2001)	22	1968–1996	Global
IEA (2000)	21	1994–1998	Japan
	16	1976–1984	Global
	47	1984–1987	Global
	21	1987–1996	Global
Surek (2005)	20	1976–2003	Global
IEA (2011)	22.8	1976–2003	Global
IEA (2011)	19.3	1976–2010	Global

[a] Note that table does not aim at providing a fully comprehensive review of the literature, but rather an indication of the range of learning rates estimated to date. For a wider dataset refer to [4].

The differences in learning rates between different studies and between different time periods are significant given that changes in the assumed learning rate greatly affect projected cost reductions, estimated capacity expansion needed to reach a given target cost and the possible timing for such an achievement [4,25]. This sensitivity becomes clear when using learning rates to estimate the cumulative production required to achieve particular cost reduction targets. For example, Ferioli et al. estimated that reaching a cost target of 0.05€/kWh under a learning rate of 22.5% would require an installed production capacity of 90 GW, whereas under an only moderately reduced learning rate of 20.2%, this more than doubled, to 190 GW [25].

Similarly, uncertainties in the rate of market growth greatly affect the estimated date by which cost reduction targets will be achieved. For example, in a rare study which developed separate experience curves for c-Si and thin film, Trancik and Zweibel [18] estimated thin film PV capital costs ranging between 0.5 and 0.7 $/Wp over the next decade to 2022, under different market growth assumptions.

Table 2
Experience curves production cost projections.

Study	Year of study	PV technology	Cost projection and year	Cumulative production projection
Surek	2005	c-Si	1$/Wp by 2023	75 GWp
Van Sark et al.	2010	c-Si	0.8–1€/Wp by 2013	49–96 GWp
Trancik and Zweibel	2006	Thin film	0.7$/Wp by 2022	29 GW (thin film)

Note: Historic cost forecasting estimates have not been adjusted for currency and inflation. Thus, they are to be interpreted here as relative rather than absolute values. Currency years coincide with the year of the study.

Table 3
Comparison of current and previously estimated production cost targets (€/Wp).*Source*: [32,33].

Study	2010	2011	2013	2015	2020	2030
c-Si						
EU PV Tech Plat (2007)			1		0.75	
EU PV tech Plat (2011)		1[a]		< 1	< 1	
Thin film						
EU PV Tech Plat (2007)	1–1.5				0.75	0.5
EU PV Tech Plat (2011)		0.75–1.2[a]			0.5	< 0.5

Note: currency years coincide with the years of the studies, i.e. respectively 2007 and 2011.
[a] Actual figures.

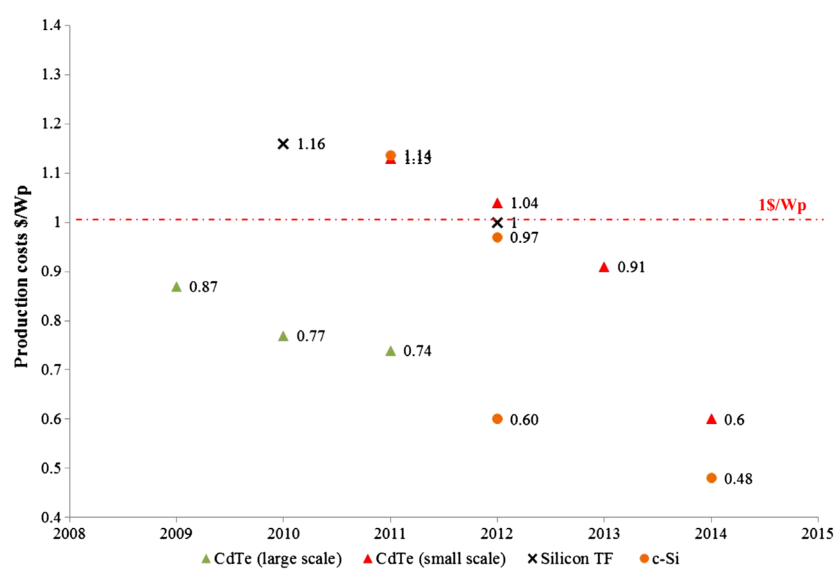


Fig. 3. Current and forecasted production costs for c-Si and thin film (CdTe and Silicon thin film). *Note*: Data from 2013 onward is industry and analysts' forecasts and as such should be treated with caution. Two 2012 data points are presented for c-Si due to fast cost reductions achieved over the year. Currency year is the year of the first data point for each series, e.g. 2009 for CdTe (large scale) series.
Sources: [36–41,78].

Given these sensitivities and uncertainties, projections vary considerably in the forecasting literature and, unsurprisingly, have not always coincided with actual outcomes. An early 2000s study from Schaeffer et al. found that a range of cost reduction forecasts made before 2000 were too optimistic, with forecasts made in the 1980s projecting costs for 1990 which weren't realised until the 2000s [9]. Over the last decade, by contrast, forecasts have tended to underestimate cost reductions. For example, Tables 2 and 3 present cost projections from experience curves studies for c-Si and thin film PV [4,15,18].

The cost targets in Table 2 relate to widely shared assumptions of 'threshold' production costs of 1$/Wp and/or 1€/Wp across the PV cost reduction literature over the last decade. In practice, production costs for c-Si and thin film technologies were already close to, or already below, the 1$/Wp threshold by 2011 (see Fig. 3) and for a cumulative production capacity of just 37 GWp (of which just 5 GWp was for thin film) [43] – i.e. much earlier and for a considerably lower worldwide production capacity than that forecasted by the experience curve studies.

Moreover, it is important to notice how the use of module prices as proxy of production costs further complicates the use of experience curves as a tool for analysis of drivers behind costs and price trends and as a forecasting technique. Evidence presented in the previous section clearly highlights how PV module prices have been greatly affected by market supply/demand dynamics in the last decade of high market growth. Such forces go well beyond the learning-by-experience effects emphasized by experience curve analysis. Indeed, industry strategies and supply–demand imbalances are likely to have been a greater influence on the recent dramatic fall in PV module prices than underlying production cost reductions.

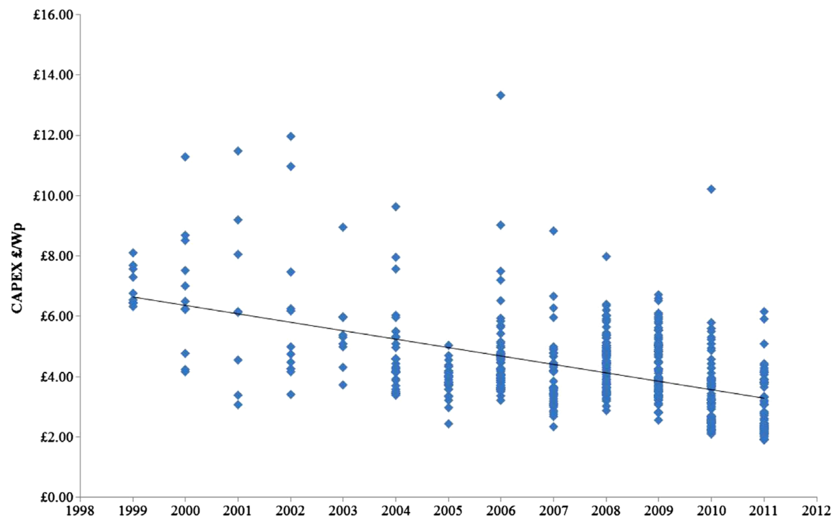


Fig. 4. PV system price across European countries. *Note*: Data is converted to 2011 British pounds, accounting for currency exchange rates and inflation. *Sources*: [83–97].

3.3. Engineering assessment of PV technologies

As with experience curves, engineering assessments of PV technology costs carried out up to early-2000s were generally over-optimistic [9], predicting costs for the end of the 1990s, which were only realised a decade later. Equally, more recent engineering studies have *underestimated* cost reductions. For example, Table 2 compares estimates of target cost reductions for c-Si and thin film technologies presented in EU PV 'Technology Platform' roadmaps produced in 2007 and updated in 2011 [32,33]. The comparison shows how estimates of both c-Si and thin film future costs had already been realised by 2011; it also shows that future targets were reduced in the updated roadmap.

4. Trends in PV system prices

Although modules are a major cost element (accounting for around 35–55% of total PV cost, depending on applications [79–82]), the appropriate measure for PV costs competitiveness is the system capital price (CAPEX),[3] i.e. including balance of system cost (BOS). The discussion in this section focuses on PV system price rather than cost, because of data availability.

Fig. 4 presents CAPEX of PV systems installed in several European countries over the last decade (Germany, Italy, Spain, Netherlands, Belgium, Austria, Greece, France and the UK). The price variability shown in Fig. 4 reflects a range of technological, market and contextual factors. System CAPEX does not scale linearly with system size, but tends to be lower in commercial systems and large utility scale systems [98,99]. It also differs with system type, with, for example, BIPV (buildings integrated) systems being more expensive than standard roof top applications. Despite this variability, Fig. 4 shows a clear trend toward decreased system price over time.

Overall, PV system costs reveal a compound learning system. Price reductions have arisen from the combined effect of several factors, including system design modifications (such as reducing the number of BOS parts, improving mechanical and electrical integration of PV modules, and improving mounting systems for easier, faster and cheaper installation); BOS component standardization (allowing for higher production volumes and economies of scale, and to shift system assembly from the field to the factory); and reduced 'area-related' BOS costs associated with module efficiency increases [32,33,44,100].

System cost reductions are also correlated with PV market expansion [98,99,101]; a more developed PV market will tend to be characterized by:

- Greater competition among system developers and installers, which reduces margins
- The development of an experienced network of installers and wholesale distribution networks, capturing learning by doing in installation, and economies of scale along the supply chain;
- Greater purchasing power of system developers and installers for module and system components. For example, PV module prices are considerably lower in countries with well-developed markets and supply chains[4] [102].
- More transparent and efficient administrative rules and grid connection procedures, reducing transaction and financing costs due to delays in installation and connection (IEA, 2011).

To highlight the correlation between reduced PV system costs and market expansion, Fig. 5 presents system CAPEX and total installed capacity across selected EU countries (Germany, Italy and UK).[5] Germany and Italy are large and leading PV markets; market expansion in Germany has been driven by Feed in Tariffs (FIT) and 'soft loan' schemes introduced in 2004, preceded by roof-top deployment programs [94,103]. Similarly, Italy introduced FITs in 2006 and, once initial scheme implementation issues were resolved, started experiencing a major PV market expansion in 2008, becoming the largest world market in 2011 [47,61].

As Fig. 5 shows, for a given module price, system price is lower in countries with larger PV markets. For example, in 2007 and 2008 (years of massive market expansion in Germany [104]) average system CAPEX in Italy were about 30% higher than in Germany (e.g. 4500£/kW versus 3600£/kW in 2007). Italian and German system prices converge in 2010–2011, as the Italian annual market reaches the GWs size. A similar pattern is evident for the UK. For example, in 2007 the average UK system price for a standard roof top c-Si

[3] CAPEX figures are presented instead of levelised cost of electricity (LCOE), as the latter vary considerably according to the type of PV system assumed and they are location and country specific.

[4] PV module prices have been 90% and 180% of global average module price in countries with PV markets above 100 MW/y and below 5 MW/y, respectively.

[5] Similar patterns are reported in the USA, as highlighted in [98,99,101]

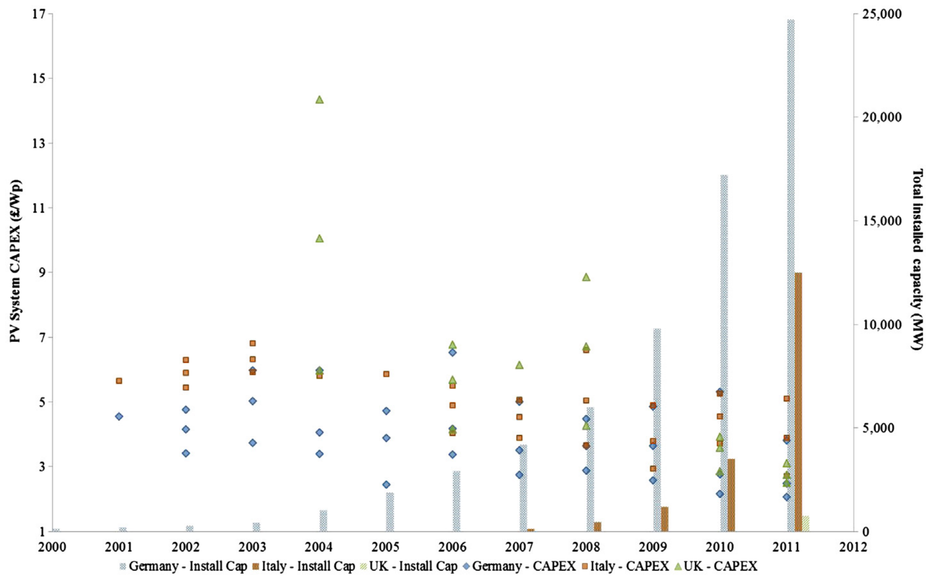


Fig. 5. PV system prices against total installed capacity in Germany, Italy and UK. *Note*: Average, min and max system CAPEX figure are plotted for each country, when more than one figure was available. Data is converted to 2011 British pounds, accounting for currency exchange rates and inflation.
Sources: [83–97].

system was 5821€/kWp, while in Germany system integrator SolarWorld quoted 4500€/kWp (3487£/kWp) for a similar system [85]. In addition, the installation and commissioning share of the total system price was about 19% in the UK and 6.2% in Germany [85], probably reflecting lower competition and a less developed and experienced network of system developers and installers in the UK [85,105]. Since 2010, UK experienced a dramatic drop in system prices after the introduction of a FIT scheme (installed PV capacity grew from about 30 MW in 2008 to 750 MW by 2011 [47]), and average system price dropped to £2.75 in 2011.[6]

The rapid convergence of UK system prices to those in more developed PV markets also suggests a fluid knowledge spillovers across countries for BOS learning, with newer markets able to benefit quickly from other countries' experiences [9]. Clearly, reaping the benefits of such knowledge spillovers and transfer can only be seen if sufficiently powerful market creation policies are put in place.

4.1. Predicting national PV system prices – the case of the UK

As pointed out in Section 2.1, the contextual variability of PV system CAPEX limits the use of established cost forecasting methods for PV system price predictions. In particular, forecasting is even more uncertain in countries with a nascent PV sector, where robust time series of historical PV system prices are not available. Nonetheless, evidence on future PV system CAPEX trajectories is needed to assess cost competitiveness of PV technologies and to inform national energy policy decisions, in particular in deciding the level of remuneration needed to stimulate capacity growth while also avoiding windfall profits stemming from support levels exceeding the real requirements [6]. For example, future system price trends are crucial in setting the right level of support tariff under a Feed in Tariff scheme: a feed in tariff should offer a predictable profitability level to potential investors, but should also follow PV price dynamics in order to minimize the overall cost of the scheme and to guarantee constant rate of return (i.e. avoid excessive profit making) [106–108]. To exemplify the implications of this challenge the analysis here focuses on the recent UK PV policy and market experience.

Fig. 6 presents UK PV system future price trajectories as estimated by several studies commissioned by the UK Government since 2008 [80,109–111]. In terms of forecasting method, such estimates can be categorized as engineering assessment as they appear to be based on a mix of data gathering and experts' elicitation. Trajectories are presented for small, medium (when available) and large size PV systems. The figure shows how previous estimates of PV system CAPEX have underestimated price reduction achieved in the UK over the last couple of years and how estimates for future price reductions trajectories have been progressively revised downward. For example, 2012 UK PV system prices had been estimated in 2008 to be £3338/kWp and £3115/kWp respectively for small and large PV systems [110], much higher than the actual out-turns of respectively £2542/kWp and £1200/kWp for the same PV system sizes [80]. Similarly, estimates for UK system costs in 2020 for e.g. small size systems have been revised downward from £2172/kWp in the 2008 study [110] to £1050/kWp in the 2012 study [80].

In other words, evidence presented in Fig. 6 points out how UK system price reductions achieved in the last couple of years were largely unexpected. While international module price decreases played an important role, evidence suggests that UK PV system prices have fallen further than would be expected from a 'module-only' effect,[7] with reductions of over 50% in the medium and large scale PV segment between early 2010 and mid-2012 (respectively about 54% and 64% [80,109], which compares to reduction in average global module prices of about 45% over the same period [46]). Thus, some national learning has accrued in the UK through market expansion.

The unexpected change in PV prices has had implications for policy making in the UK, as the Government has been forced to quickly revise PV Feed in Tariffs in order to follow price reduction, avoid excessive profits and minimize the cost of the scheme [112,113].

[6] In the available data set, average UK system prices are lower in 2006 compared to 2008. This is a data source artefact: 2006 system prices come from the DTI Large Scale Field Trial statistics, i.e. they represent systems of medium size [96], whereas 2008 data comes from the Low Carbon Building Programme statistics, i.e. mainly residential systems of small size [93]. The former are on average cheaper than the latter, as system price does not scale linearly with system size.

[7] Similar trends have been found in US PV system prices [98,99,101].

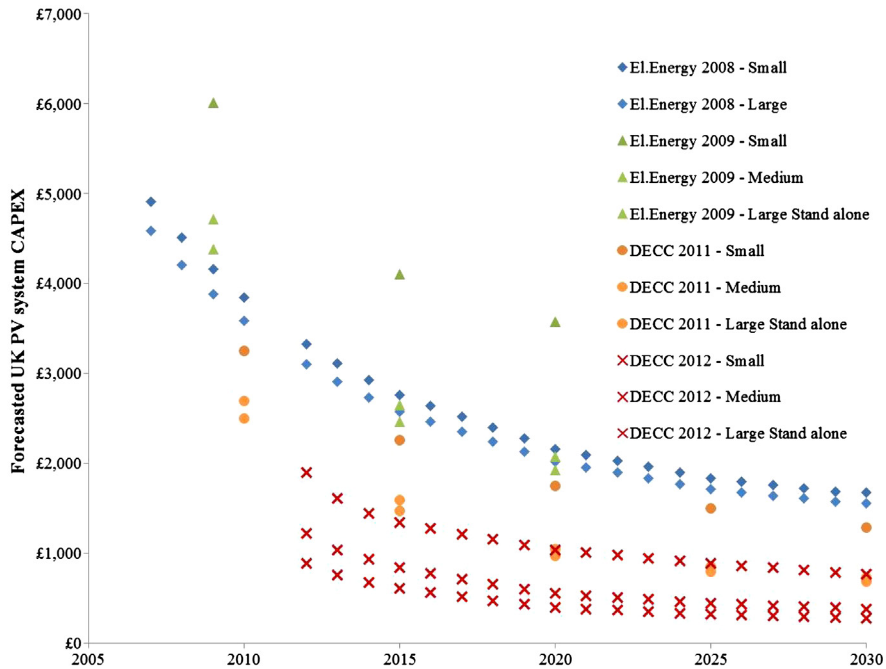


Fig. 6. Forecasts of UK PV system CAPEX, comparison of 2008–2012 estimates. *Note*: Data is converted to 2011 British pounds, accounting for currency exchange rates and inflation.
Source: [80,109–111].

However, the tariff revision process created substantial uncertainty in the UK PV market, leading to increased investment risk and creating a less favorable environment for the development of a nascent UK PV market [42,114,115]. Thus, the UK experience points out the importance for policy making of accurate predictions of future PV system costs.

5. Discussion and conclusions

The broad concern of this paper has been the challenge of representing technological innovation and energy technologies cost reductions trajectories in scenarios of long term system change, in the face of multiple uncertainties – including uncertainties over short timescales. These challenges have been discussed and addressed by considering recent changes to performance, cost and price for solar PV. While historical trajectories describe a sustained long term reduction in PV technologies costs over time, both at module and system level, a closer look reveals alternating periods of cost/price stabilization and reduction rather than steady progress along a prescribed curve. From a long term, historical perspective these short term variations are 'averaged out' over sufficiently long timespans, but for researchers and policymakers concerned with understanding technology learning and cost trajectories over short timescales, no such ironing-out can be afforded.

At module level, historical trajectories describe a significant long term reduction in PV technology cost and price over time. Production costs have been steadily reducing, thanks to the combination of multiple factors, including devices R&D innovation, incremental improvements of manufacturing processes, increased manufacturing size and economies of scale. Recent history also shows strong links and causal relationship between market creation policies, PV sector demand and supply dynamics, supply chain bottleneck, industry responses and price reductions. In particular, the largely unexpected PV module prices drop experienced in the last couple of years is strongly correlated with the dramatic market growth experienced by the PV sector, the impressive production capacity expansion in China and a consistent market oversupply. The analysis has shown how disentangling production costs driven module price reductions from market demand/supply dynamics is not always straightforward. Improved resolution of the performance-cost-price dynamics in conventional PV is a critical area for further research, with powerful implications for policy, in particular in terms of the relative role of demand pull versus technology push/niche market support measures.

When PV price trends are framed at the system rather than module level, the range of influences and interactions involved is multiplied, with system learning resulting from the combined effect of several technical and non-technical factors. In particular, the impact of market expansion on prices, which has been a powerful driver at the module level, is also evident at the system level, with evidence presented here indicating a strong correlation between system CAPEX reductions and national market expansion – driven by local/national BOS learning effects, alongside the more well-known international module price reductions. The relative role of national BOS learning versus international module price dynamics in defining future PV system CAPEX trends, and the implications for policy (for example, in defining the level of policy support) are key areas for further research (see for example, [116].

Overall, the rapidly changing dynamics of PV price, cost and performance and the complex mix of underlying drivers, present deep challenges for technology forecasting tools. Neither the aggregated nor disaggregated studies reviewed here anticipated well the dramatic recent changes affecting PV – both experience curve and engineering based studies were, at different times, overly optimistic or overly cautious.

Experience curves are essentially aggregated observations, manifest in simple functional relationships of complex underlying causes. As is well recognized in the research literature, their use in future-oriented studies is laden with problems. While explicit uncertainty treatment helps ameliorate some of these concerns (for example, by systematic sensitivity and scenario analysis), simple experience curve studies are historically based indicators of trends rather than incisive tools for cause and effect analysis over shorter timescales. As the PV case here presented

demonstrates, their use is especially problematic in the more volatile and unstable conditions of an international energy sector responding to accelerated change imperatives.

Engineering based assessments provide more detailed accounts of technology performance and cost characteristics, including for those novel technologies for which historical data is not available. However, their reliance on a mix of data and expert judgement is also accompanied by high levels of uncertainty. They also often embed an assumption of the primacy of technical innovation on technology performance and cost. The evidence presented on PV cost trajectories indicates a strong influence of non-technical forces such as scale economies, market supply–demand dynamics and industry structure and restructuring.

For forecasting methods, this suggests the need to form expert judgements across a wide canvas of expertise – spanning for example international markets and finance, and business strategy expertise alongside the more technical expertise often referenced in bottom-up engineering assessments. Disentangling PV performance, cost and price dynamics is still a key issue, but one to which experience curves studies cannot readily respond. Evidently, for example, by using module prices as a cost proxy they cannot discriminate between cost trajectories from price trends, at least over short timescales. Moreover, although the analysis and evidence presented here shows the importance of market expansion in PV cost and price reductions (both at module and system level), the relative contribution of market creation policies alongside other forces (including demand/supply imbalances, country specific industrial policies and industry strategies) needs to be carefully monitored overtime.

Information about costs and prices of a newly deployed technology such as PV can in principle be revealed through short-run market activity [42], particularly where robust historical data is absent, as in the case of emerging novel technologies or nascent national PV market. However, accurate ex-ante estimation of technologies costs and prices remains a priority, as it is crucial in defining a balanced policy strategy to support emerging energy technologies, as PV. Indeed, technologies' cost forecasts are needed to inform decisions on supply push policy for technologies still far from commercialization (such as novel PV technologies) and to define the correct level of demand pull support needed to stimulate capacity growth of more mature technologies (such as c-Si PV). The latter in particular would allow minimizing the occurrence of sudden, short term policy changes driven by unexpected technology price dynamics and, in turn, the overall uncertainty in the energy policy framework (as clearly exemplified by the recent PV policy developments in the UK).

This is a challenging agenda. In their different ways, both experience curves and engineering assessments are oriented to long term learning effects (learning by experience and learning by research, respectively), rather than the more immediate, volatile and often country specific forces which have shaped PV cost and price trends over the past decade (such as scale effects, market dynamics, industrial re-organization). In the present context of heightened pressures for energy system change and accelerated energy innovation, these less gradual forces may become more powerful contributors to energy technology learning. For technology forecasting the challenge is for improved methods better able to capture the diversity of learning effects at work, and their interactions with policy, so as to better inform policy support for innovation in the overall project of energy system transformation.

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